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Influence of Micro-texture Parameters on Bone Drilling Force and Torque: A Finite Element Model

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Abstract. The micro-texture on the tool surface is an effective way to improve the quality of the drilling. While high-performance micro-texture plays an important role in improving the quality of working surface and prolonging the life of tool. In this study, a three-dimensional finite element model was established to study the relationship between drilling thrust, torque and microstructure parameters (micro-pit depth, micro-pit diameter and micro-pit spacing) during drilling of cortical bone. The model was validated by cortical bone drilling using a micro-structured tool. On basis of this, the thrust and torque prediction models of the micro-texture parameters were obtained. The results indicate that the thrust and torque increased with the increase of micro-pit diameter; while the increase of the micro-pit spacing caused the thrust and torque to decrease. When the depth of the micro-pit increased, the thrust and torque decreased first and then increased, and we found that the effect of micro-pit spacing and micro-pit depth on force and torque is insignificant.

1. Introduction

Bone drilling as an essential step in bone surgery, widely used in various types of orthopedic surgery. Excessive drilling thrust force and torque can raise the drilling temperature, which leads to bone necrosis, as well as poor pore quality that is important to stable screw fixation. Therefore, optimization of thrust force and torque is an important part of clinical problems. Karaca [1] concluded that spindle speed, thrust force and bone density were significant parameters in affecting temperature and borehole quality by an integrated multidisciplinary vitro experiment. Vishal Gupta [2] interpreted how to measure force and torque in the course of surgical drilling into bone. In order to reduce the thrust force and torque during drilling process, a number of researchers have conducted that the effect of different methods on thrust force and torque [3].

In recent years, with the development of micro-texture in the field of tribology, the micro-texture on the tool surface can improve the quality of the surface, extend tool life and improve tool cutting performance. Many researchers have begun to study the application of micro-texture in the field of cutting [4,5]. Shen Dian analyzed the whole process of periodic changes of the surface friction coefficient of the micro-texture, and revealed the friction mechanism of the micro-texture [6]. Andersson's study showed that under the condition of oil lubrication, the micro-texture can significantly reduce the surface friction and wear [7].



Previous studies showed the surface micro-texture which can improve the friction between the interface and reduce the friction coefficient [8]. In this paper, a simulation model of micro-texture drill in drilling the cortical bone was established. And an experimental platform for drilling cortical bone with a micro-texture drill was built to verify the correctness of the model. Then analyzed the relationship between drilling thrust, torque and micro-texture parameters during the process of drilling cortical bone, and a prediction formula of thrust force and torque was given with the response surface method.

2. Experimental procedure

2.1 Sample preparation

Medical twist drills were selected as drilling tool for this study, the parameters of them are shown in Table 1. Surface texture with different parameters on the minor flank which was close to the side-cutting edge of the twist drill was made by laser machining (type: YLP-F20), Figure 1 shows the geometric model of the micro-texture twist drill.

Table 1. The geometric parameters of micro-texture twist drill

diameter (mm)	point angle	helix angle	chisel edge angle
4	118°	25°	125°

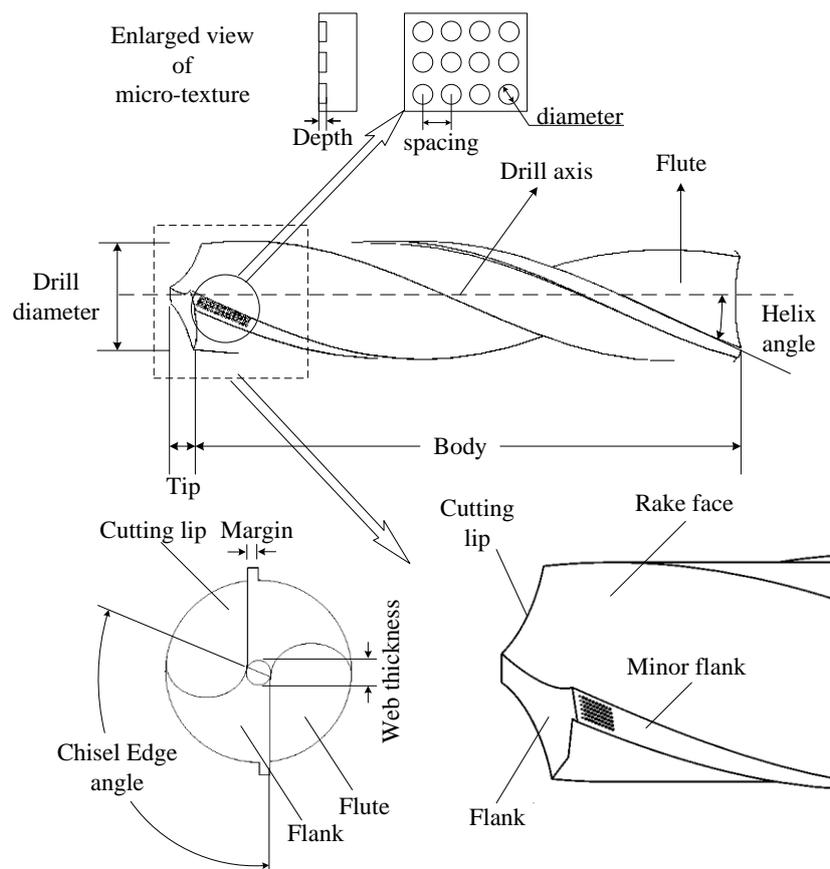


Figure 1. Geometric model of micro-texture twist drill.

The samples of cortical bone were the male pig bones which were obtained from the local butcher, because of its close resemblance to human bones, and the tests were performed within 2 h after the specimens of bone were obtained [9,10].

2.2 Experimental platform

An experimental platform of bone drilling was designed as shown in Figure 2. Hanchuan Machine Tool XK714D was used, the thrust force and torque were measured by a three-channel Kistler dynamometer.

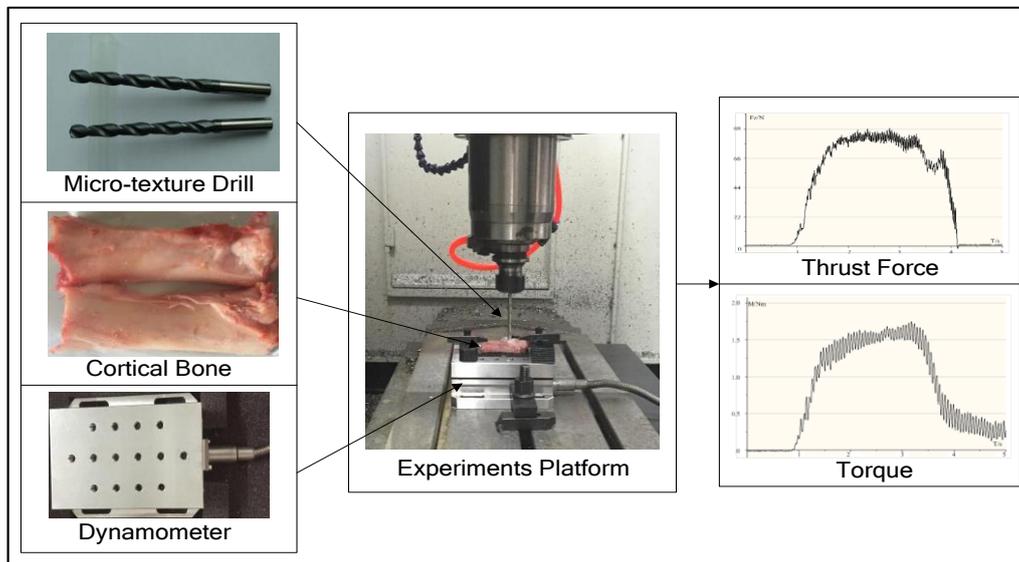


Figure 2. Experiments platform of bone drilling (drill diameter:4mm, drill speed:900rpm, feed rate:60mm/min).

The experiment adopted three kinds of medical twist drills with different micro-texture parameters, which were processed by laser marking machine, and the micro-texture parameters are shown in Table 2.

Table 2. Parameters of micro-texture on the minor flank of drill

Group	Depth(μm)	Diameter(μm)	Spacing(μm)
A	20	80	150
B	20	90	200
C	30	80	200

2.3 FE model of bone drilling

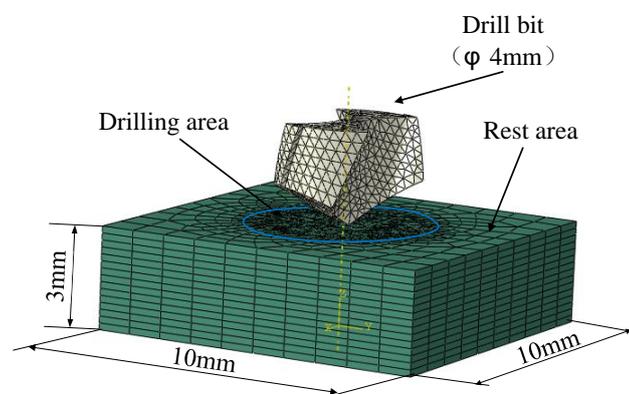


Figure 3. The mesh of the cortical bone and the twist drill.

A geometric model of micro-texture twist drill with complex surface was established by UG is shown in Fig.1, the geometric parameters are shown in Table 1. Since the changes of complex forms of bone on the simulation results are negligible, a simplified geometry of bone is used for the simulation and

the results are satisfying [11]. In this model, a solid cuboid is used for the bone, with a thickness of 3 mm and length of 10 mm (Figure 3). The material properties [12] of cortical bone and twist drill used in the model are shown in Table 3.

Table 3. Material properties of the cortical bone

Properties	Values
Density (t/mm^3)	2.0×10^{-9}
Young's modulus (Mpa)	2.0×10^4
Poisson's ratio	0.36
Specific heat capacity ($\text{mJ t}^{-1} \text{K}^{-1}$)	1.64×10^9
Thermal conductivity ($\text{W m}^{-1} \text{K}^{-1}$)	0.56

In this paper, the samples of cortical bone were considered as an elastic-plastic material with nonlinear strain hardening, the Johnson-Cook material model that accounts for the strain rate sensitivity and temperature effect was used for the cortical bone [13]:

$$\sigma_Y = (A + B\varepsilon_p^n)(1 + C \ln \varepsilon^*)(1 - T^{*m}) \quad (1)$$

Where A, B, C and n are constants and $T^* = \frac{(T - 298)}{(T_{melt} - 298)}$; σ_Y is effective stress; ε_p and ε^* are

the effective plastic strain and strain rate, respectively; and the T_{melt} is melting temperature. The model parameters [14,15,16] of the cortical bone are shown in Table 4.

Table 4. Johnson-Cook parameters of the cortical bone

A (MPa)	B (MPa)	C	n	m	T_{melt}
50	101	0.03	0.08	1.03	1300

As for the meshing, two kinds of mesh density were used for bone to improve the accuracy of calculation and reduce the processing time. The significant part of the cortical bone involved in the calculation was the area that contacts with the twist drill. Therefore, its mesh was refined. While for the rest of bone model, a low mesh density was enough. The mesh of the cortical bone and the twist drill was shown in Figure 3.

2.4 Simulation verification

Drilling thrust force and torque with different micro-texture parameters are obtained by the experiments of bone drilling, which are compared with the results of simulation to modify the finite element model. The results are shown in Figure 4.

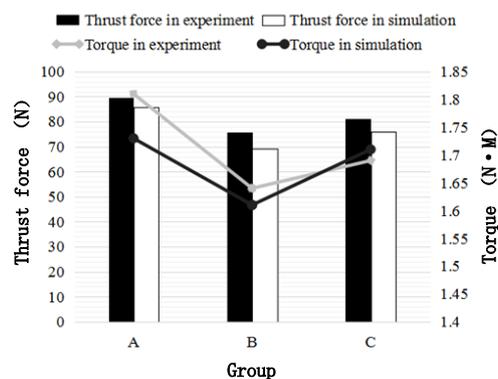


Figure 4. Results of simulation and experiment.

It can be concluded from Fig. 4, the experimental values are similar to the simulated values, so the simulation model is reliable, which provides the basis for the parametric study of micro-texture.

2.5 Experimental design based on response surface methodology

Response surface method (RSM) is an important statistical method to solve the multi-variable problem by using regression equation analysis to find the optimal target parameters [17]. Center composite design (CCD) is the most commonly used RSM. It can provide many information about experimental variables and experimental errors with the least number of experimental cycles. The five grades of all variables in CCD are represented by code $(-\alpha, -1, 0, +1, +\alpha)$. where (0) , $(-\alpha)$ and $(+\alpha)$, represent the average, the minimum and the maximum, respectively. The independent variables and their related levels and codes are shown in Table 5. In the study, three factors are associated with micro-texture parameters.

Table 5. Coding and level of design factors

Factor	Levers				
	-1.68	-1	0	+1	1.68
Depth (μm)	13.18	20	30	40	46.82
Diameter(μm)	73.18	80	90	100	106.82
Spacing(μm)	99.55	120	150	180	200.45

Table 6. DOE results for thrust force and torque for bone drilling process

Simulation no.	Design factors			Simulation results	
	Depth (μm)	Diameter (μm)	Spacing (μm)	Thrust force (N)	Torque (N m)
1	46.82	90	150	75.4	1.53
2	20	80	180	85.8	1.68
3	30	100	150	69.3	1.48
4	30	90	150	69.3	1.48
5	30	90	150	69.3	1.48
6	30	73.18	150	79	1.58
7	40	100	120	76	1.57
8	40	80	120	92.9	1.71
9	30	106.82	150	58	1.39
10	20	100	120	75.4	1.54
11	20	100	180	62.1	1.41
12	30	90	150	69.3	1.48
13	40	80	180	83.2	1.62
14	20	80	120	94.7	1.73
15	40	100	180	63	1.43
16	30	90	150	69.3	1.48
17	30	90	150	69.3	1.48
18	30	90	200.45	69.7	1.49
19	30	90	99.55	81.2	1.61
20	13.18	90	150	73.2	1.52

A total of 20 runs and corresponding response data designed by CCD can be expressed as Table 6.

The empirical model is fitted with the response data. In this paper, a quadratic model is suitable to determine a critical function point using Equation (2):

$$y = \beta_0 + \sum_{i=1}^k \beta_i x_i + \sum_{i=1, j=1}^k \sum_{i < j}^k \beta_{ij} x_i x_j + \sum_{i=1}^k \beta_{ii} x_i^2 + \varepsilon \quad (2)$$

Where y is the predicted response; k is the number of variables; x_i , x_j is the design variable; β_0 is the constant term; β_i is the coefficients of the linear terms x_i ; β_{ij} is the coefficients of the quadratic terms $x_i x_j$, and ε is the residual associated with the experiments.

3. Results and discussion

3.1 Development of mathematical models

To obtain the relationship among micro-texture parameters and thrust, torque, we obtain the perform response data obtained from 20 simulation runs and use regression to generate an approximate mathematical model. Equation (3), (4) represent the regression response surface models of the thrust force and torque that can be expressed as follows:

$$F_Z = 229.328 - 1.858H - 1.133D - 0.414L + 13.686 \times 10^{-3}HD - 1.25 \times 10^{-4}HL - 9.625 \times 10^{-4}LD + 0.023H^2 + 3.102 \times 10^{-3}D^2 + 1.465 \times 10^{-3}L^2 \quad (3)$$

$$M = 3.235 - 0.023H - 0.014D - 3.336 \times 10^{-3}L + 8.125 \times 10^{-5}HD - 1.25 \times 10^{-5}HL - 1.625 \times 10^{-5}LD + 2.38 \times 10^{-4}H^2 + 4.182 \times 10^{-5}D^2 + 1.588 \times 10^{-5}L^2 \quad (4)$$

where F_Z is the thrust force; M is the torque; and D , L , H are the micro-pit diameter, spacing, and depth, respectively.

3.2 Analysis of variance (ANOVA)

In this paper, ANOVA analysis was used to test the quadratic model. The results of the analysis of variance for the quadratic model of thrust are shown in Table 7. The result shows that the value of R^2 is 0.9637, it means that 96.37% of the total variations were explained by the model. The model F-value of 7.4 indicated the significance of the regression model. The P-values of the developed model, which were less than 0.05, indicated that the model terms were statistically significant and the model was credible. The model items with a P-values greater than 0.1 have no significant impact on our research. Similarly, the results of the variance analysis of the quadratic model of torque are shown in Table 8. It shows that the value of R^2 was 0.9721, the P-values less than 0.005.

Table 7. Variance analysis of the thrust force

Source	Sum of Squares	Degree of freedom	Mean square deviation	F-value	P-value
Model	1546.19	9	171.8	7.4	0.0022
H	5.65	1	5.65	0.24	0.6323
D	975.42	1	975.42	42.02	0.0027
L	299.03	1	299.03	12.88	0.0049
HD	4.35	1	4.35	0.19	0.6742
HL	0.031	1	0.031	1.35E-03	0.9715
DL	7.41	1	7.41	0.32	0.5845
H ²	75.18	1	75.18	3.24	0.1021
D ²	22.19	1	22.19	0.96	0.3512
L ²	193.35	1	193.35	8.33	0.0162
Residual	232.11	10	23.21		
Missing item	232.11	5	46.42		
$R^2=0.9637$					

Table 8. Variance analysis of the torque

Projects	Sum of squares	Degree of freedom	Mean square deviation	F	P
Model	0.15	9	0.017	7.39	0.0022
H	4.74E-004	1	4.74E-004	0.21	0.6593
D	0.090	1	0.090	39.24	<0.0001
L	0.027	1	0.027	11.93	0.0062
HD	2.113E-003	1	2.113E-003	0.92	0.3602
HL	3.125E-004	1	3.125E-004	0.14	0.7200
DL	2.122E-003	1	2.122E-003	0.92	0.3602
H ²	8.163E-003	1	8.163E-003	3.55	0.0887
D ²	4.033E-003	1	4.033E-003	1.76	0.2147
L ²	0.023	1	0.023	9.89	0.0104
Residual	0.023	10	2.298E-003		
Missing item	0.023	5	4.595E-003		
$R^2=0.9721$					

3.3 Model fitness check

Residual analysis was used to study the accuracy of the model. The normal probability plots for the residuals of thrust force and torque can be seen in Figure 5(a) and (b), respectively. We concluded that the points on the normal probability plots of the residuals should be a straight line when the model was adequate. Consequently, the quadratic model with regard to the micro-texture parameters could be used to determine optimal values.

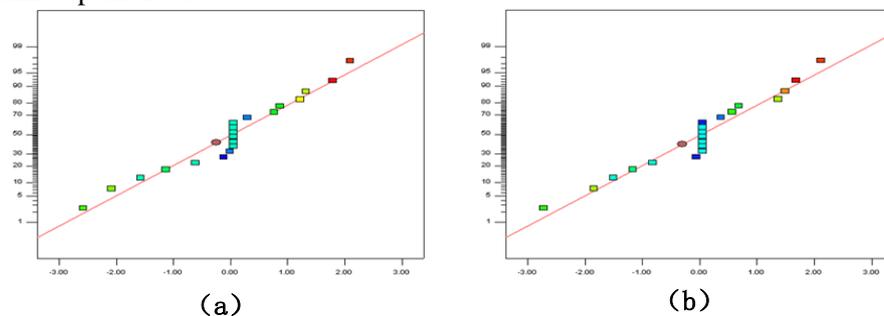
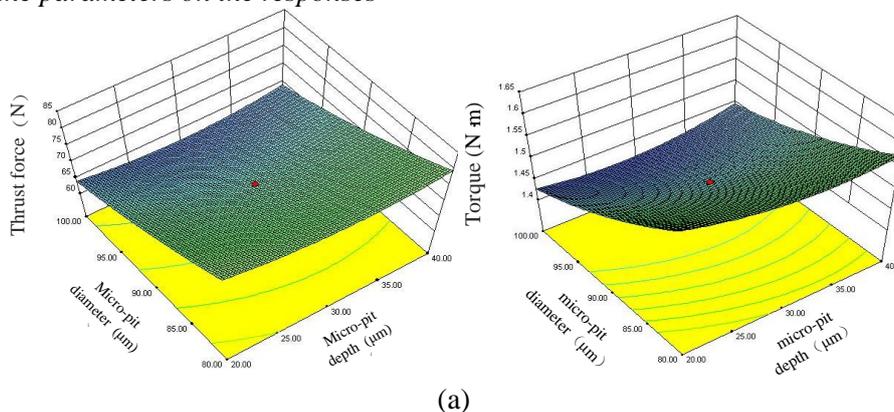


Figure 5. Normal probability plots for the residuals of thrust force and torque.

3.4 Effect of the parameters on the responses



(a)

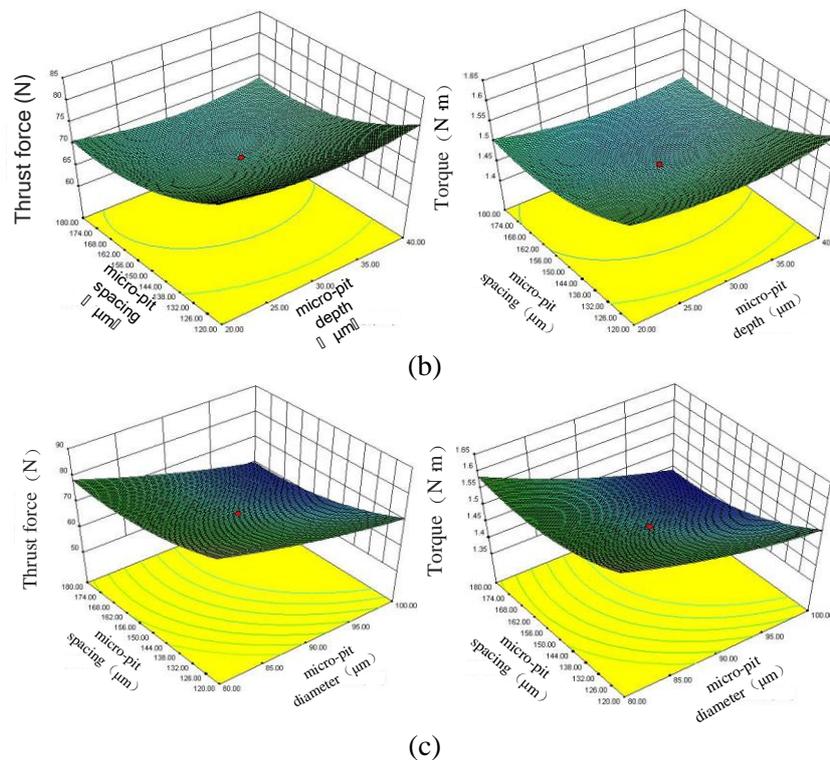


Figure 6. Interaction effects of micro-texture parameter on thrust force and torque.

Effects of the micro-texture parameters on the thrust force and torque were mathematically expressed through Eq. (3) and Eq. (4). To visualize these effects, the 3D surface profile of the interaction between the parameters by Design Expert is as follows in Fig.6.

Figure 6(a) shows the surface plots of thrust force and torque with variation in the values of micro-pit diameter and depth. It is observed that as the micro-pit diameter increases from 80 to 100 μm , the thrust force and torque reduce further. When the diameter of the micro-pit increases, the friction state between the drill bit and the chip improves, and the contact area between the drill bit and the chip becomes smaller, thus the friction is reduced, the thrust force and torque is reduced.

Similarly, the surface plots are obtained for the thrust force and torque of micro-pit spacing and depth as shown in Figure 6(b). It is observed that as the micro-pit depth increases from 20 to 30 μm , the thrust force and torque reduce; Thereafter, as the micro-pit depth increases the thrust force and torque also raise slightly. Because the micro-pit of tool surface can store micro bubbles in the drilling process, micro bubbles can improve the friction state of contact interface, but too large or too small micro-pit depth is not conducive to the stability of micro bubbles. Further the response plots are obtained for the micro-pit diameter and spacing as shown in Figure 6(c). It is observed that as the micro-pit spacing increases from 120 to 160 μm , the thrust force and torque reduce. Subsequently the changes are not obvious. Because of the smaller micro-pit spacing, too many micro-pits may reduce the surface strength of the tool, and the surface of the tool will change from elastic-plastic deformation to plastic deformation, which reduces the thrust force and torque; When the micro-pit spacing is sufficiently large, it has merely effect on the friction state, so the change of thrust force and torque is not obvious.

4. Conclusions

In this paper, the drilling process was simulated using a general purpose finite element software ABAQUS/explicit. And this model has been proven to effectively replicate the drilling process. The thrust and torque prediction models of the micro-texture parameters were obtained, which can accurately predict the drilling thrust force and torque.

The results show that the trend of thrust force and torque is basically the same, It was observed that the thrust force and torque increased with an increase in micro-texture diameter; The thrust force and torque decreased at the beginning with an increase in micro-texture spacing then the change was negligible; when the micro-texture depth increased, the thrust force and torque decreased first and then increased, but the effect is not significant.

Acknowledgments

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